

- *Effect of strain-hardening on:*
 - properties*
 - microstructure*
- *Effect of heat treatment following deformation*
 - recovery*
 - recrystallization*
 - grain growth*

Strengthening Mechanisms

Recall: strength is a measure of a materials' ability to resist plastic deformation

Review: strengthening mechanisms

effect of grain size

effect of solute atoms

effect of dislocations (strain hardening)

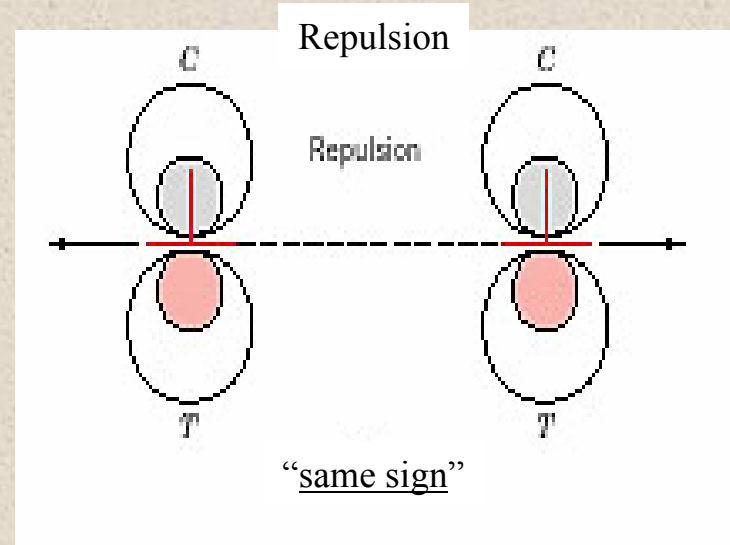
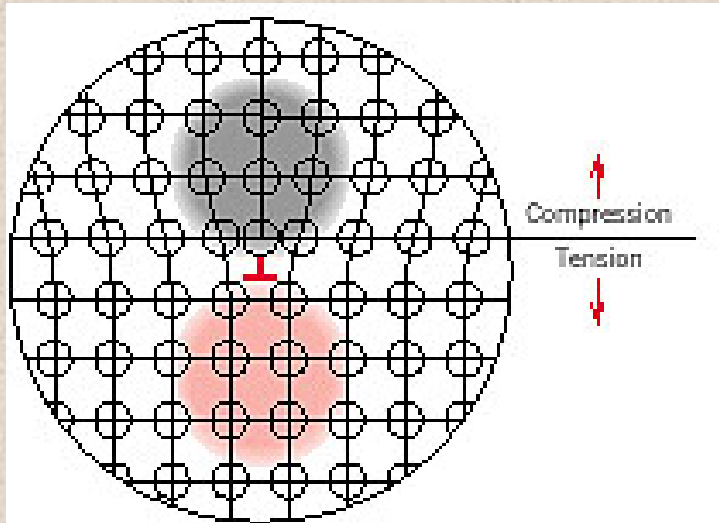


Strengthening Mechanisms (strain hardening)

- Bottom line: Strength increases with increased levels of plastic deformation.

Why?

Strengthening Mechanisms (strain hardening)



- (1) Dislocations strain fields can repulse each other.
- (2) Dislocations lines can intersect each other and become pinned.

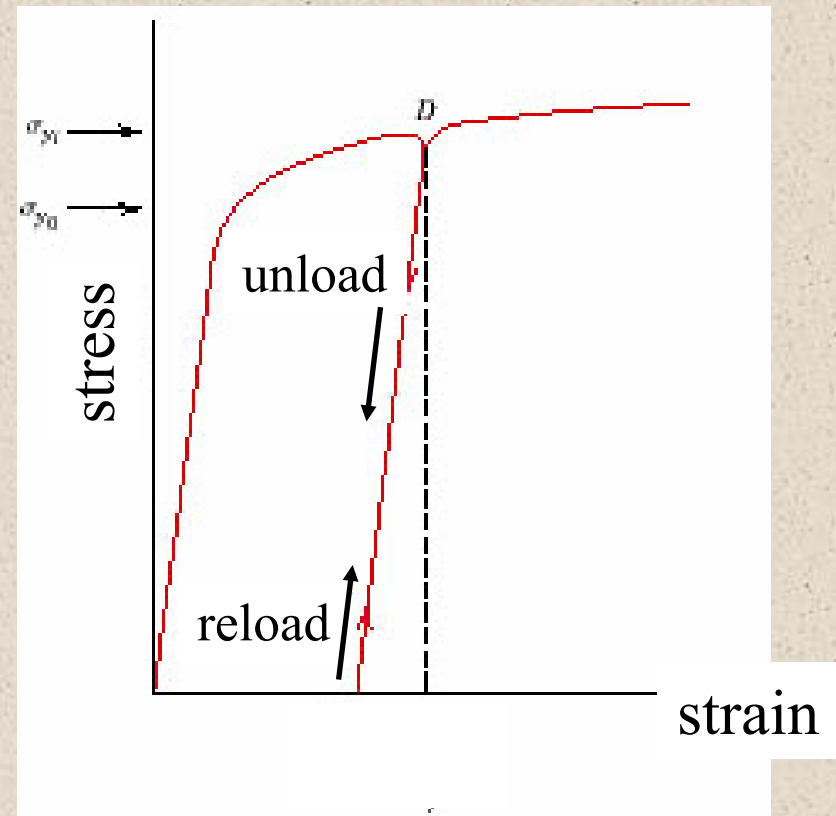
Strain-hardening
Work-hardening
Cold-working

= plastic deformation of a metal at ambient
temperature

- Cold working can be a processing method:
- Advantage: the product can become strengthened as the final shape is obtained.

• How do you cold work a material?

We've seen one way:



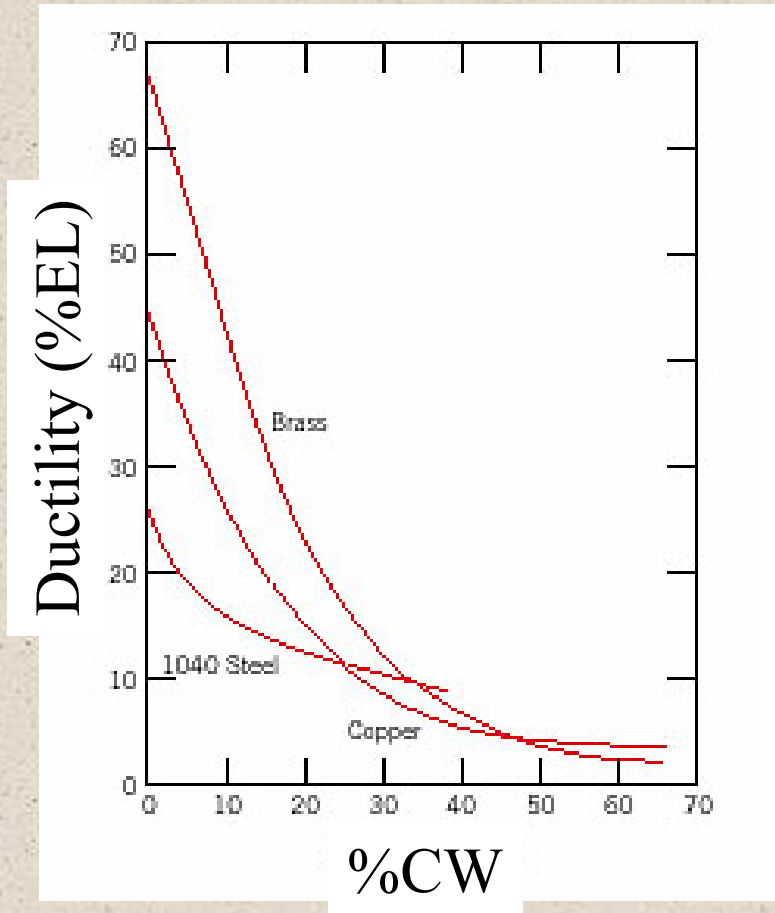
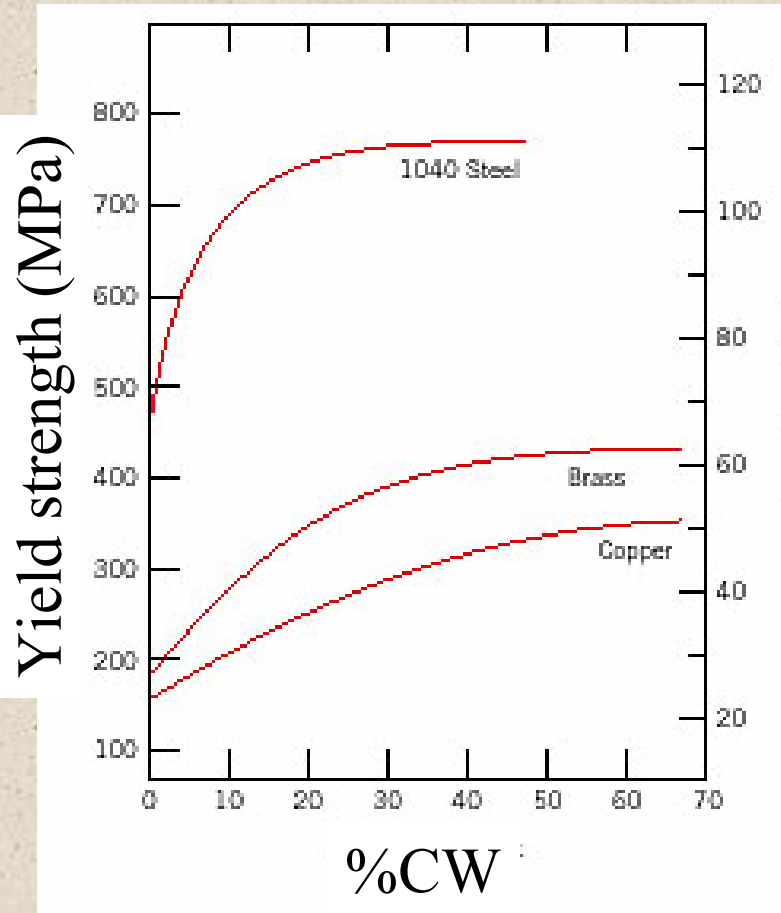
- Manufacturing processes
- Ability of a material to cold work is quantified by the strain hardening exponent

- Cold working increases yield and tensile strength.
- BUT cold work decreases ductility, electrical conductivity and corrosion resistance.

TRADEOFF!

Define: $\%CW = 100[(A_o - A_f)/A_o]$

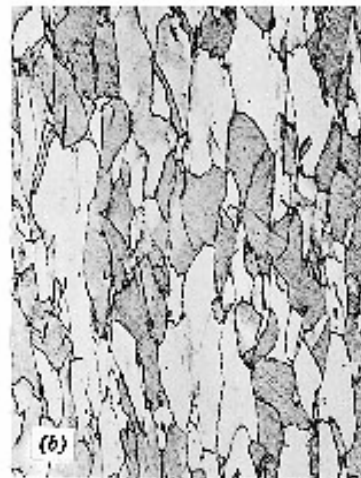
Cold working: Effect on properties



Cold working: Effect on microstructure

- Grains rotate and elongate, which introduces preferred orientations or texture.
- Preferred grain orientations cause anisotropy
- Cold working can introduce residual stress.

unstrained



strained



(Residual Stress in Glasses)

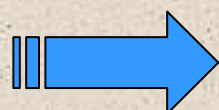
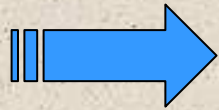
- Has nothing to do with cold working

Heat Treatment Following Deformation

Heat treatment following deformation

- Deformed material contains residual stress and strain energy
- Annealing a deformed material at high temperature can release this energy and revert material back to original state.
- Reversion at a given temperature occurs in three stages:

Recovery \Rightarrow Recrystallization \Rightarrow Grain growth

 Increasing time at temperature 

Recovery

- During recovery, diffusion occurs so as to relieve the strain energy by:
 - lowering the dislocation density
 - producing low energy dislocation configurations (polygonization)
- Residual stresses are relieved but the mechanical properties remain unchanged (stress relief annealing).
- Electrical conductivity is restored.

Recrystallization

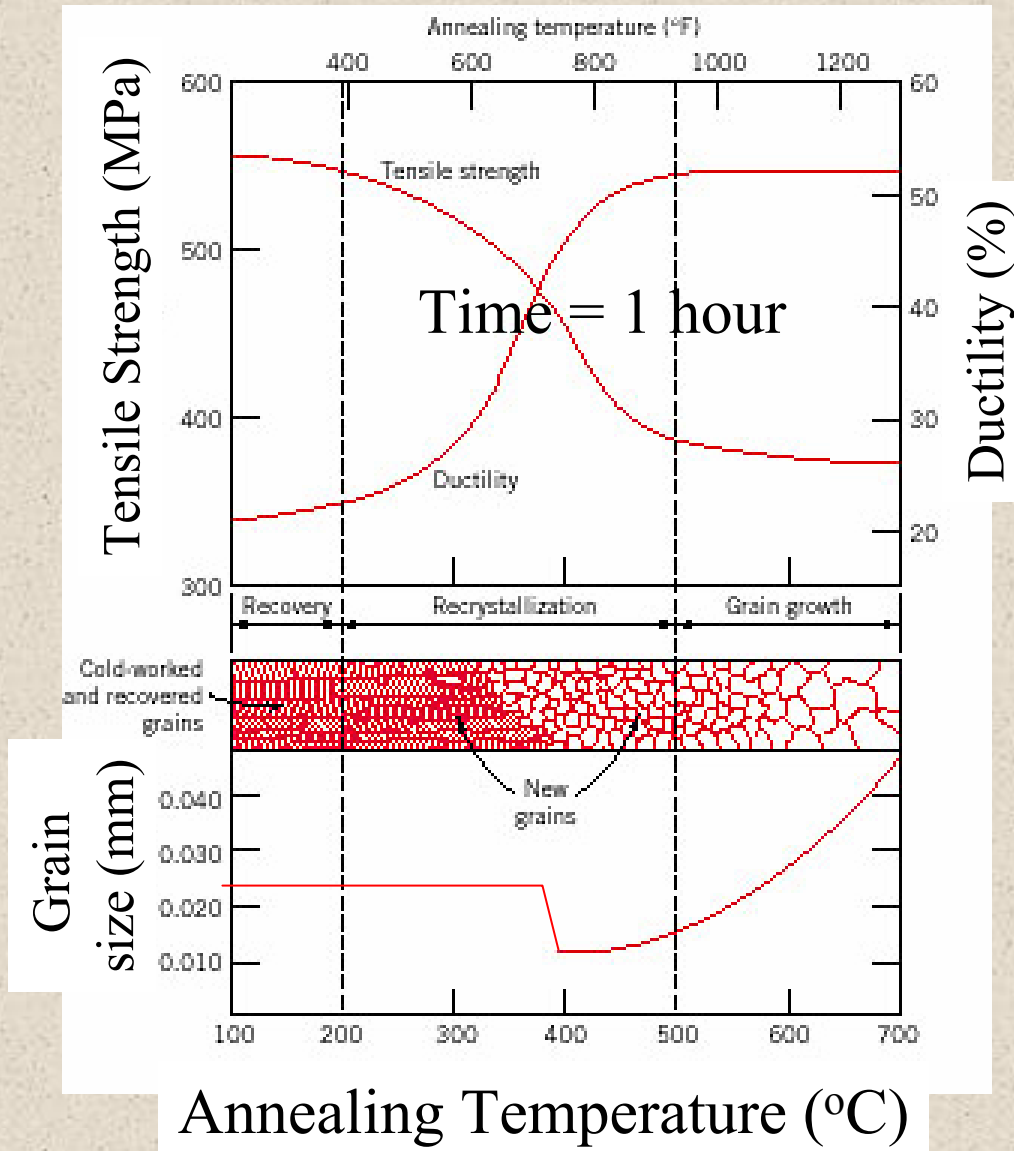
- During recrystallization, new strain-free, equiaxed grains are created and grow to replace strained material.
- Short range diffusion enables this process.
- Driving force \Rightarrow internal energy difference between strained and unstrained material.



Grain growth

- Large grains grow at the expense of smaller ones.
- Boundaries move by diffusion of atoms from one side of the boundary to another.
- Driving force \Rightarrow reduction of energy associated with the grain boundaries.

Effect of Annealing Temperature



Recrystallization

temperature needs to be defined for a particular time (i.e., T at which recrystallization is complete in 1h)

Recrystallization is easier for

- high CW levels
- small CW grain size
- low melting point metals
- pure metals

Example

Cylinder of brass with 0% CW has an initial diameter of 6.4 mm and it is to be cold-worked by drawing. It is required to have a yield strength of 345 MPa, an elongation at failure of at least 20%, and a final diameter of 5.1 mm.

Design a process to obtain the desired parameters.

Hot working

- Plastically deforming a metal at a temperature above the recrystallization temperature is called hot working.
- Advantages:
 - strengthening does not occur during hot working, allowing large reductions in size.
 - imperfections are eliminated or minimized
- Disadvantages:
 - anisotropic due to uneven temperature profiles
 - poor surface finish compared to cold working (oxidation)



